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Title: Neutrinoless double beta decay and the neutrino

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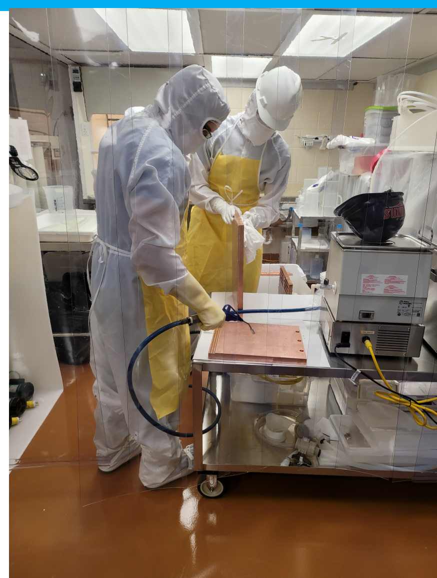

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Neutrinoless Double Beta Decay and the Neutrino

Steve Elliott

ν and $\beta\beta$ Science
Key Technical Issues, Background
MAJORANA DEMONSTRATOR Results
LEGEND Phased approach to 1 ton

Why Neutrinos?

ν properties are critical input to many open physics questions

- Particle/Nuclear Physics
  - –Fundamental questions about the Standard Model
  - –Fundamental issues regarding ν interactions
- Cosmology
  - –Large scale structure
  - –Leptogenesis and matter-antimatter asymmetry
- Astrophysics
  - –Supernova explosions
  - –Solar burning

Why are neutrinos special among the particles?

- Because the neutrino only interacts weakly, it is a very difficult particle to study. There are many things, like its mass, we don't know.

- Neutrinos might be the ultimate neutral particle.
  - They would not be distinct from their antiparticles.
  - If so, we classify them as Majorana particles.
- They might also be Dirac particles.
  - Like the charged quarks and leptons.

- The difference between these two possibilities greatly influences how the neutrino is incorporated into the Standard Model.

We know ν mix

The weak interaction produces ν_e, ν_μ, ν_τ. (flavors)

These are not pure mass states but a linear combination of mass states.

As a ν propagates, it can oscillate between flavors. This requires non-degenerate mass eigenstates.

For example, ν_μ's might be produced in an accelerator beam dump, but ν_e's might be detected some distance away.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation experiments indicate that ν mix and measure $U_{\alpha i}$.

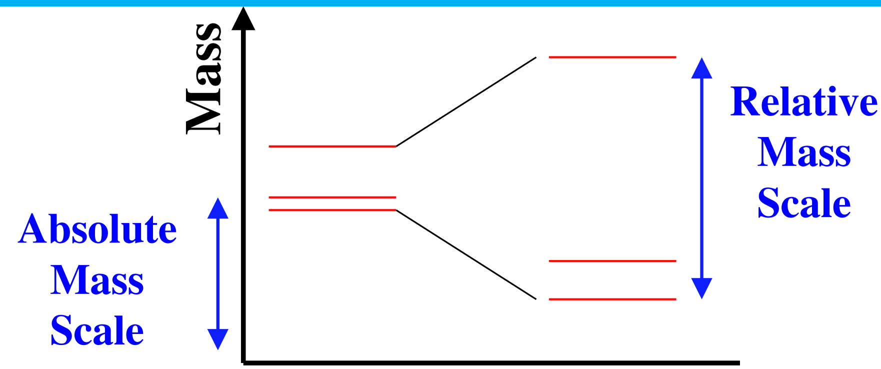
So, what do we know about neutrino masses?

- The results of oscillation experiments indicate ν do have mass!, set the relative mass scale, and a minimum for the absolute scale.

- β decay experiments (KATRIN) set a maximum for the absolute mass scale.

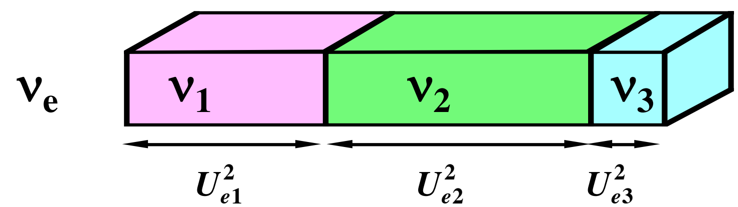
$$50 \text{ meV} < m_\nu < 800 \text{ meV}$$

What do we want to know about neutrinos?



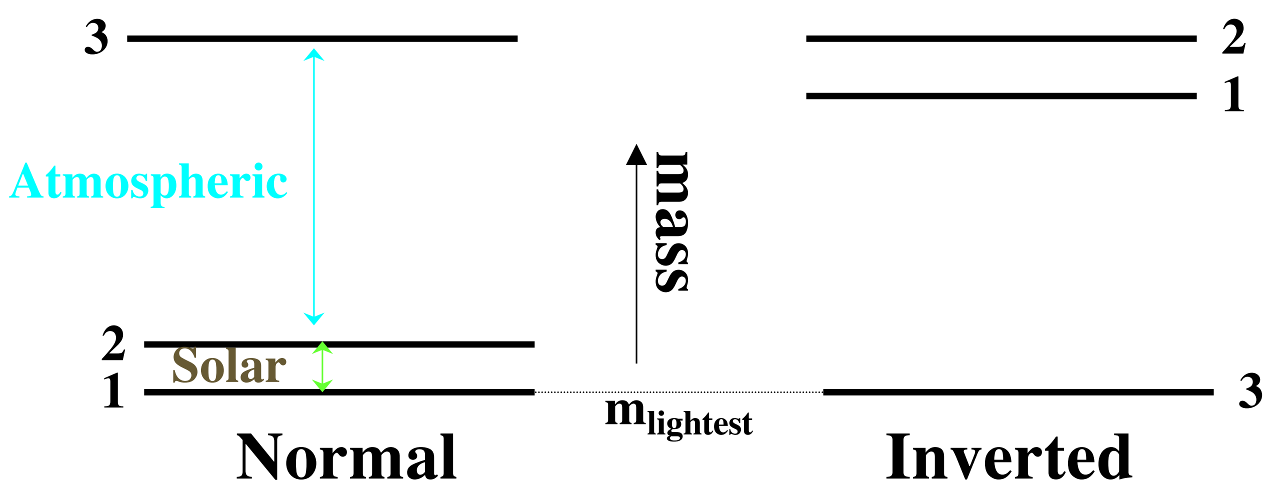
Dirac or Majorana

$$\begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \\ \bar{\nu}_{\downarrow} \\ \bar{\nu}_{\uparrow} \end{pmatrix} \text{ or } \begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \end{pmatrix}$$



Mixing

We understand some, but not all, of the ν mass spectrum



Convention: ν_e is composed of a large fraction of mass eigenstate ν_1.
What we don't know is whether ν_1 is the lightest ν.

What is ββ?

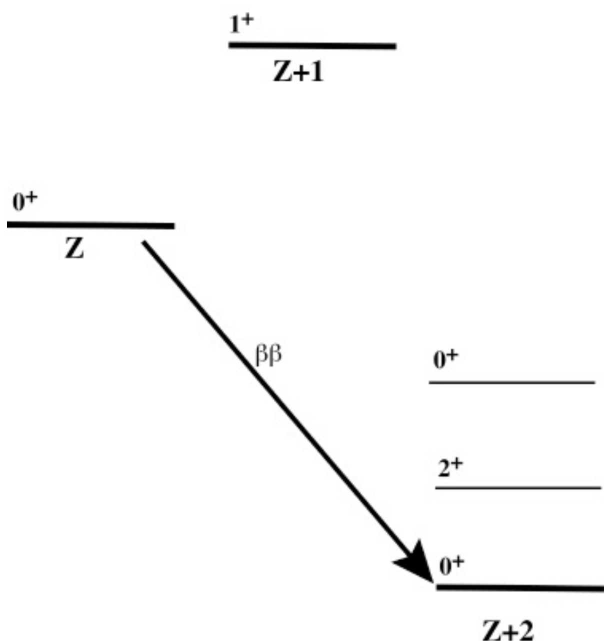
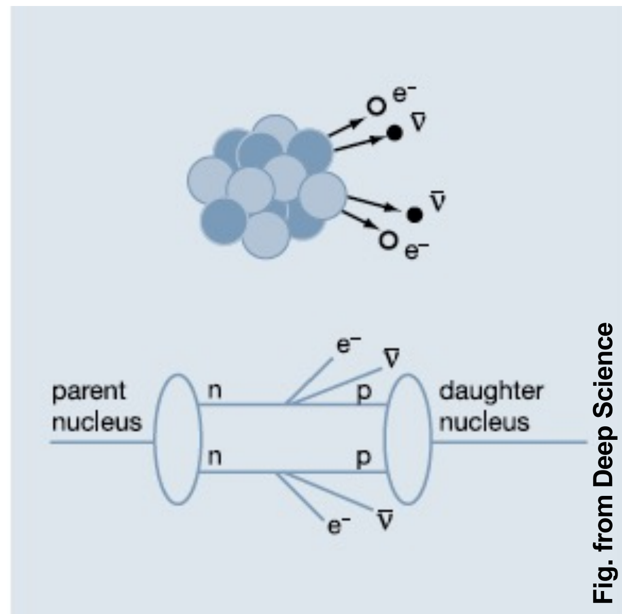


Fig. from arXiv:0708.1033



What is ββ?

$n \Rightarrow p + e^{-} + \bar{\nu}_e$ $\nu_e + n \Rightarrow p + e^{-}$

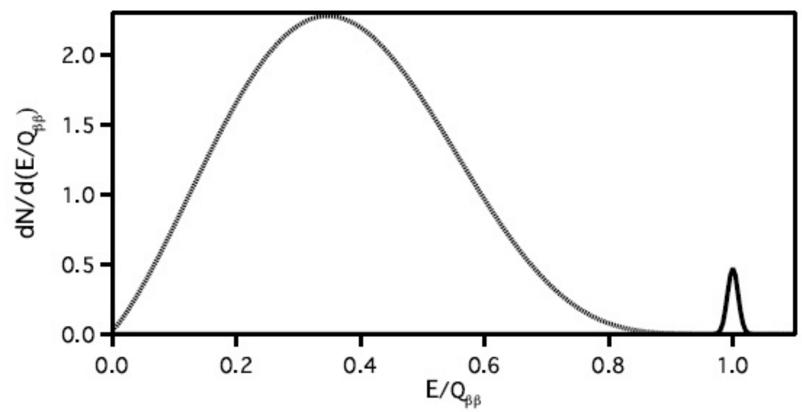
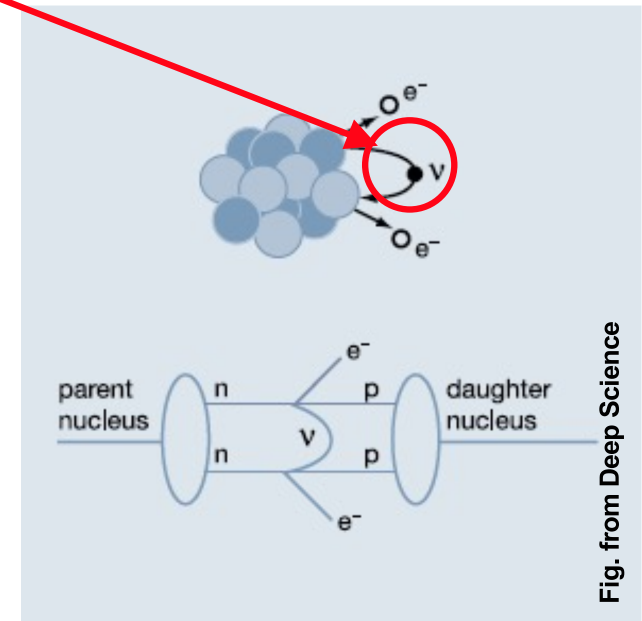


Fig. from arXiv:0708.1033



ββ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

$$\boxed{\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2}$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.

What about mixing, m_ν & $0\nu\beta\beta$?

No mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

virtual ν exchange $\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} U_{ei}^2 m_i$

Compare to β decay:

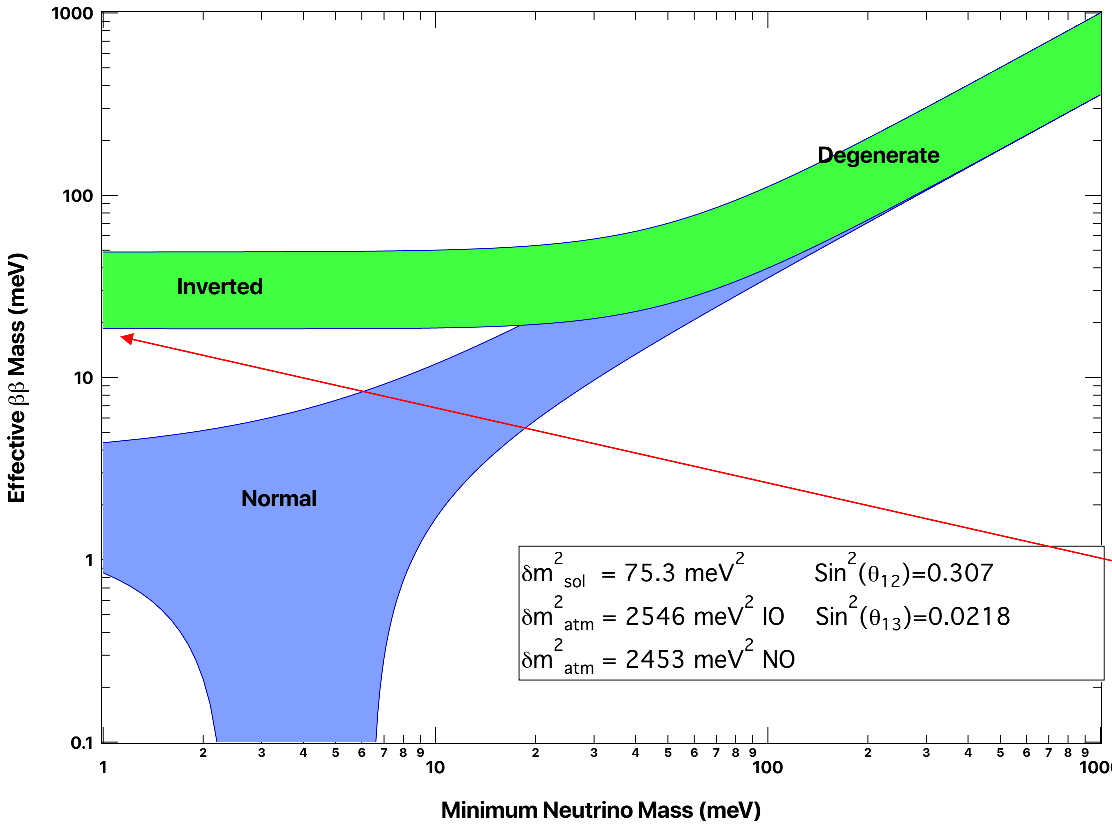
$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$ **real ν emission**

Compare to cosmology:

$\Sigma = \sum m_i$

0νββ Sensitivity

(mixing parameters from PDB-2020, without uncertainties)



Even a null result will constrain the possible mass spectrum possibilities!

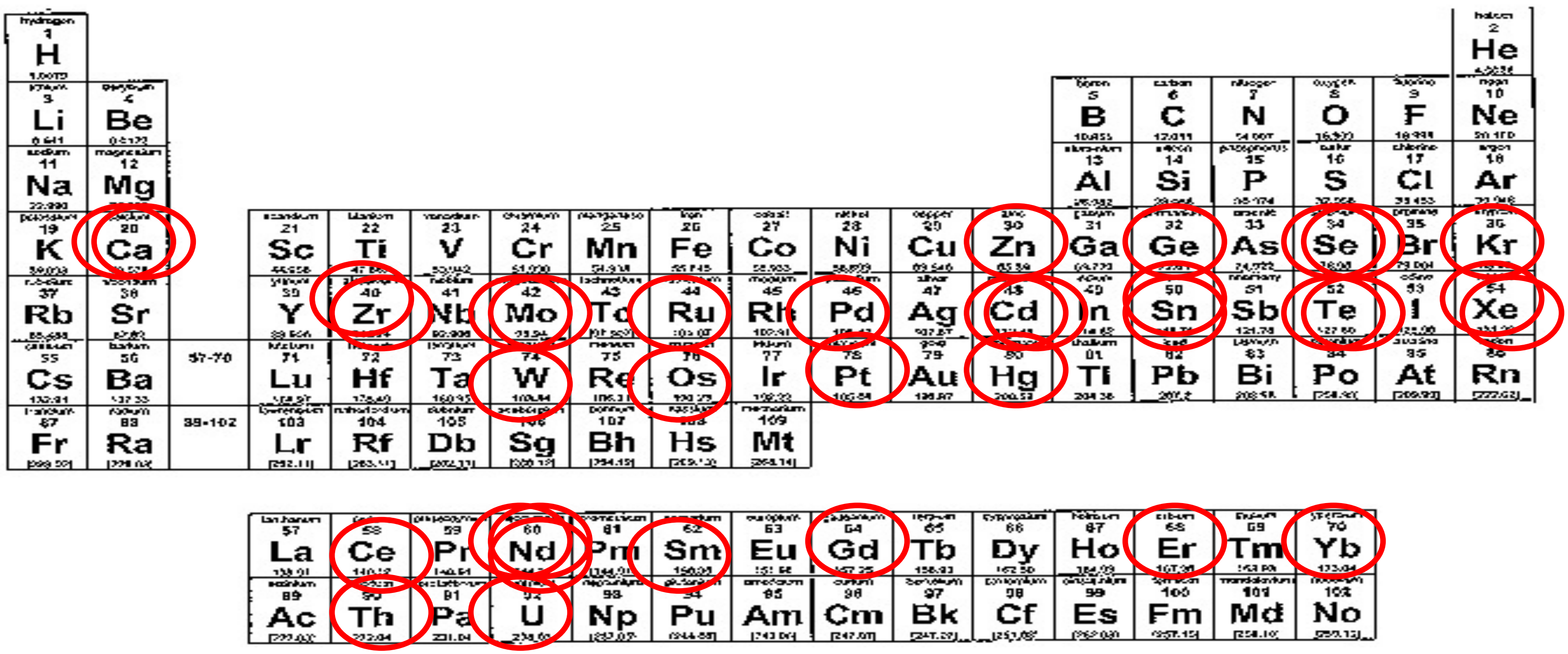
A $m_{\beta\beta}$ limit of ~18-19 meV would exclude Majorana neutrinos in an inverted ordering (IO).

ββ and the ν

- **0νββ decay rate proportional to neutrino mass squared**
  - **Most sensitive laboratory technique (if Majorana particle).**
- **Decay can only occur if lepton number conservation is violated.**
  - **May result in leptogenesis model for the matter/antimatter asymmetry.**
- **Decay can only occur if νs are massive Majorana particles.**
  - **Critical for understanding incorporation of mass into standard model.**
  - **ββ is only practical experimental technique to answer this question.**
- **Fundamental nuclear/particle physics process.**

ββ Candidate Isotopes

There are a lot of them!



So, How do we choose a $\beta\beta$ isotope?

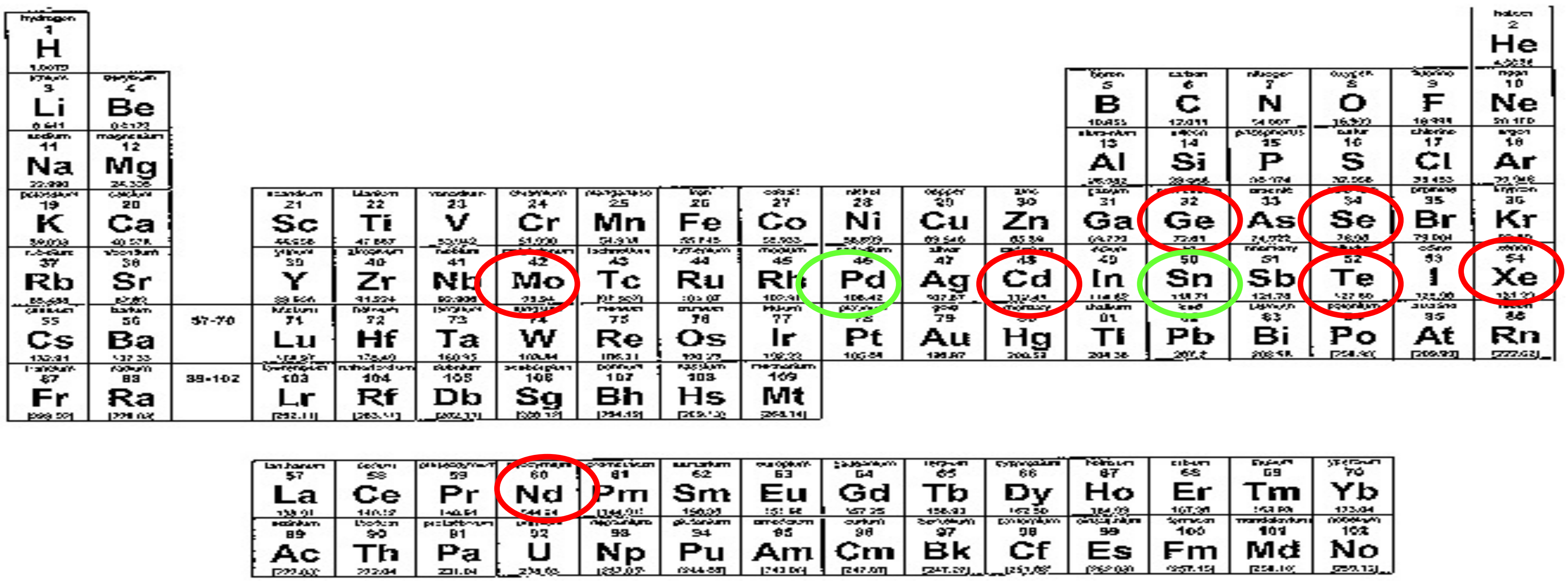
- Detector technology exists

- High isotopic abundance or an enriched source exists.

- High energy = fast rate, above background

ββ Candidates

Abundance > 5%,Trans. Energy > 2 MeV



Frequently studied isotope.

ββ History

- $2\nu\beta\beta$ rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987.
- Why did this take so long? Background

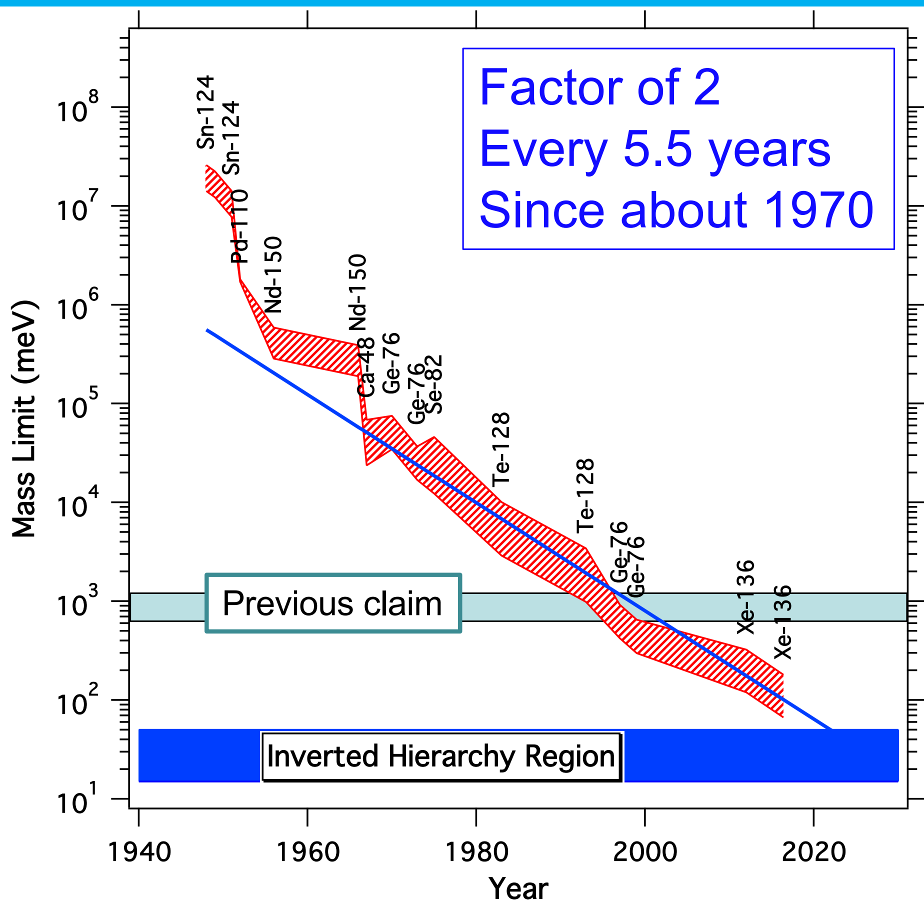
$$\tau_{1/2}(\mathrm{U, Th}) \sim T_{\mathrm{universe}}$$

$$\tau_{1/2}(2\nu\beta\beta) \sim 10^{10}\, T_{\mathrm{universe}}$$

- But next we want to look for a process with:

$$\tau_{1/2}(0\nu\beta\beta) \sim 10^{18}\, T_{\mathrm{universe}}$$

ββ History



Historically, there are > 100 experimental limits on the $T_{1/2}$ of $0\nu\beta\beta$. Here are the best constraints expressed as limits on $\langle m_{\beta\beta} \rangle$ using a range of nuclear matrix elements. Note the approximate linear slope vs. time on a semi-log plot.

By 2021, Xe and Ge provided about equal exclusion levels, although Ge is more direct at excluding claim, which is now discredited.

Toward an Ideal Future Experiment

Maximize Rate/Minimize Background

Experiment Designs are Advanced

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\Delta E}{MT_{live}} \right)^{\frac{1}{4}}$$

Experimental Parameter	Status
Large Exposure(~10 t-y)	Designs exist
Low Background (<1cnt/FWHM t-y)	Best so far is ~2, future extrapolation claims vary widely
Good energy resolution	Varies by tech., discovery potential sensitive to resol. & backgnd
Large Q value, fast $\beta\beta(0\nu)$	Ca, Ge, Se, Mo, Cd, Te, Xe
Enriched isotope	Costs & world production of raw material vary
Demonstrated technology	‘Prototypes’ in operation
Ease of operation	Demonstrated high duty cycles
High efficiency	True for most technologies
Slow $\beta\beta(2\nu)$ rate	$\beta\beta(2\nu)$ rate is slow for key isotopes and present resolutions
Identify daughter in real time	Not yet demonstrated, but some nice progress
Event reconstruction	Very nice, but detector mass is limited

Near-Term Upcoming Results

	Mass	Status
AMoRE-I	~3 kg	Running
CUORE	~200 kg	Running
EXO-200	~100 kg	Complete
GERDA I/II	~36 kg	Complete
KamLAND-Zen800	~750 kg	Running
MAJORANA	~30 kg	Complete
LEGEND-200	~200 kg	Construction-2021
NEXT	~100 kg	Construction-2022
SNO+	~120 kg	Commissioning-2022
SuperNEMO Dem.	~7 kg	Commissioning-2021

Experiments are beginning to reach below 100 meV.

$\beta\beta$ technology is ready for detectors at the ton scale. At the ton scale, the IO is a convenient goalpost.

The MAJORANA Collaboration

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MAJORANA DEMONSTRATOR

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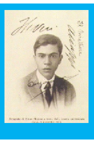
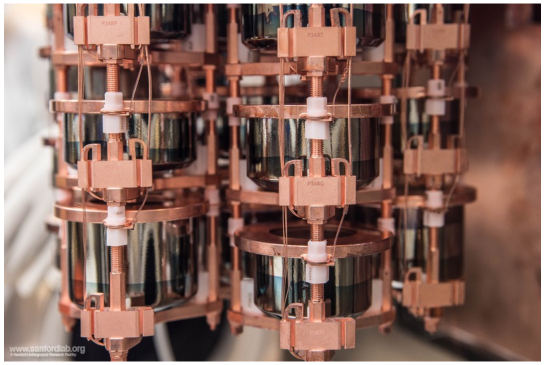


Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors and additional physics beyond the standard model

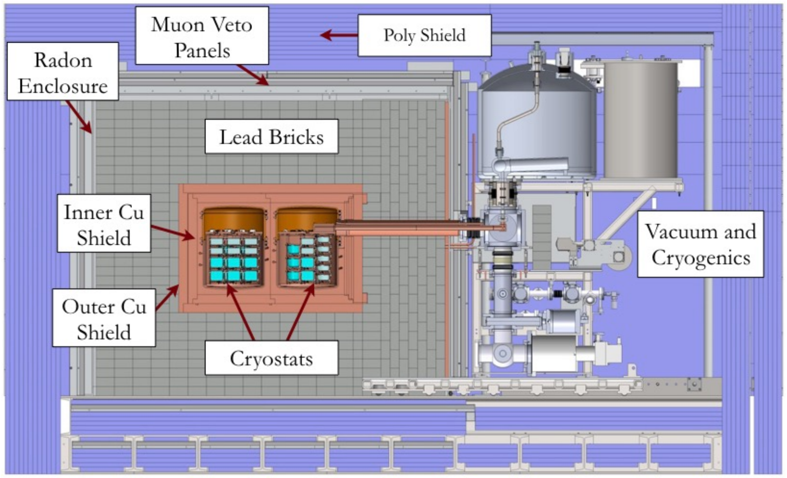


Source & Detector: Array of p-type, point contact detectors
29.7 kg of 88% enriched ^{76}Ge crystals

Excellent Energy resolution: 2.5 keV FWHM @ 2039 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Operating underground at the 4850' level of the Sanford Underground Research Facility



Apparatus Details

Two independent modules are deployed:

- A self-contained vacuum and cryogenic vessel housing the detector cryostat
- Contains a portion of the shielding
- Can be transported for assembly and deployment

Module Deployment

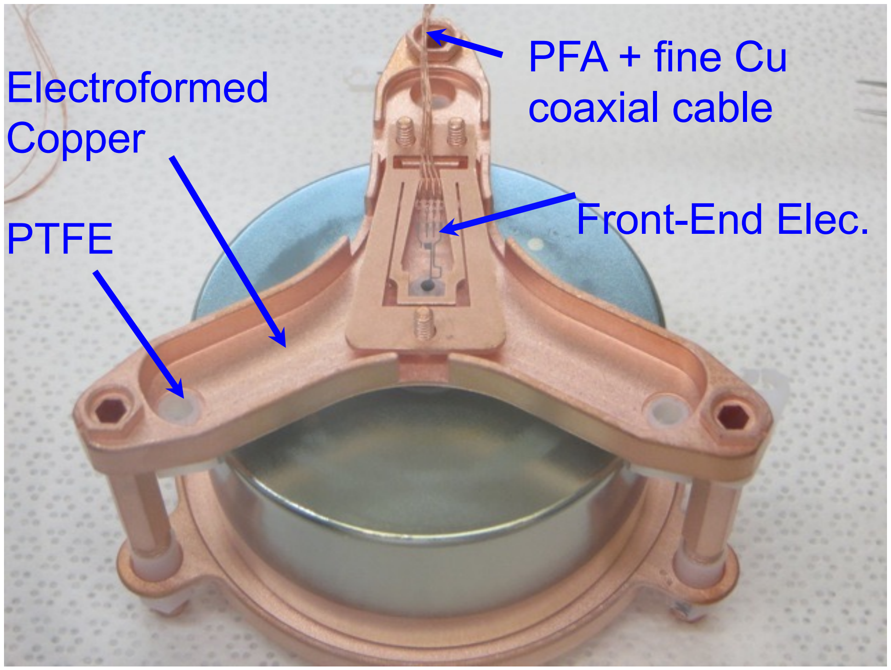
Cryostat loading

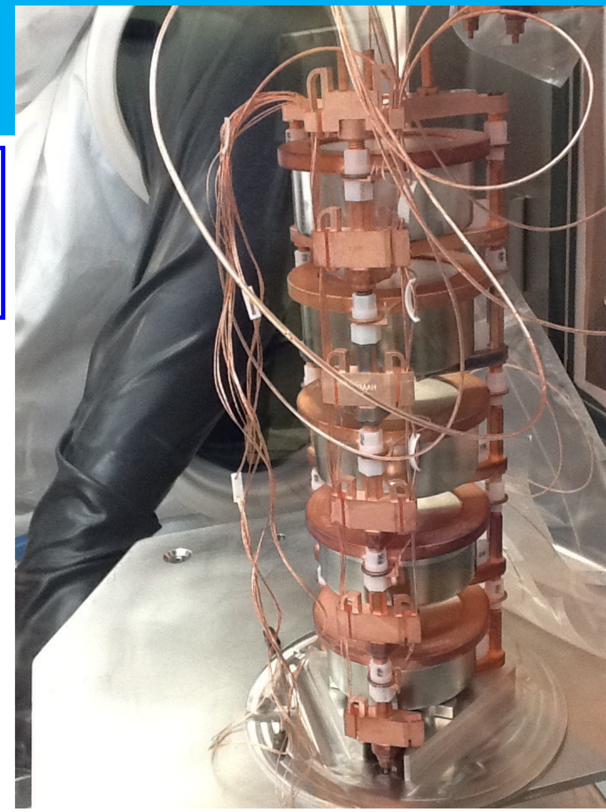
Pb and outer Cu shield

Muon active shield

Assembled Detector Unit and String

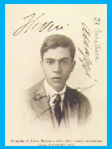
AMETEK (ORTEC) fabricated enriched detectors.
35 enriched detectors, 29.7 kg, 88% ^{76}Ge.
33 modified natural-Ge BEGe (Canberra) detectors, 20 kg.

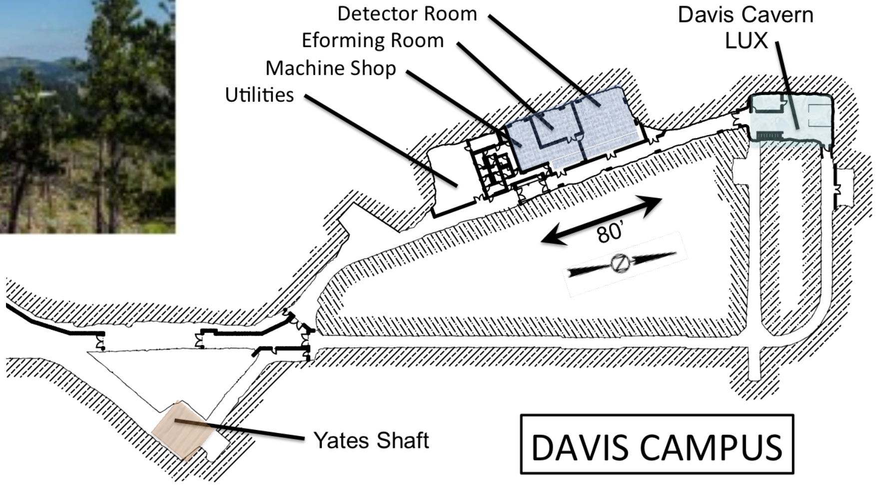




Detector assembly in N_2 purged gloveboxes.
Detectors' dimensions recorded by optical reader.

MAJORANA Underground Laboratory





4850' level, SURF, Lead SD
Clean room conditions
Muon flux: 5 x 10^{-9} μ/cm^2 s

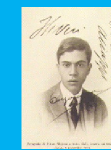
(Astropart. Phys. 93, 70 (2017))

Background Considerations
"the Usual Suspects"

- Natural occurring radioactive materials
- Environmental gammas
- $2\nu\beta\beta$
- Long-lived cosmogenics
- Neutrons

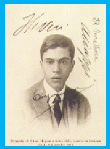
At atmospheric mass scale, expect a signal rate on the order of 1 count/tonne-year

Backgrounds Must be Both Reduced, and Rejected



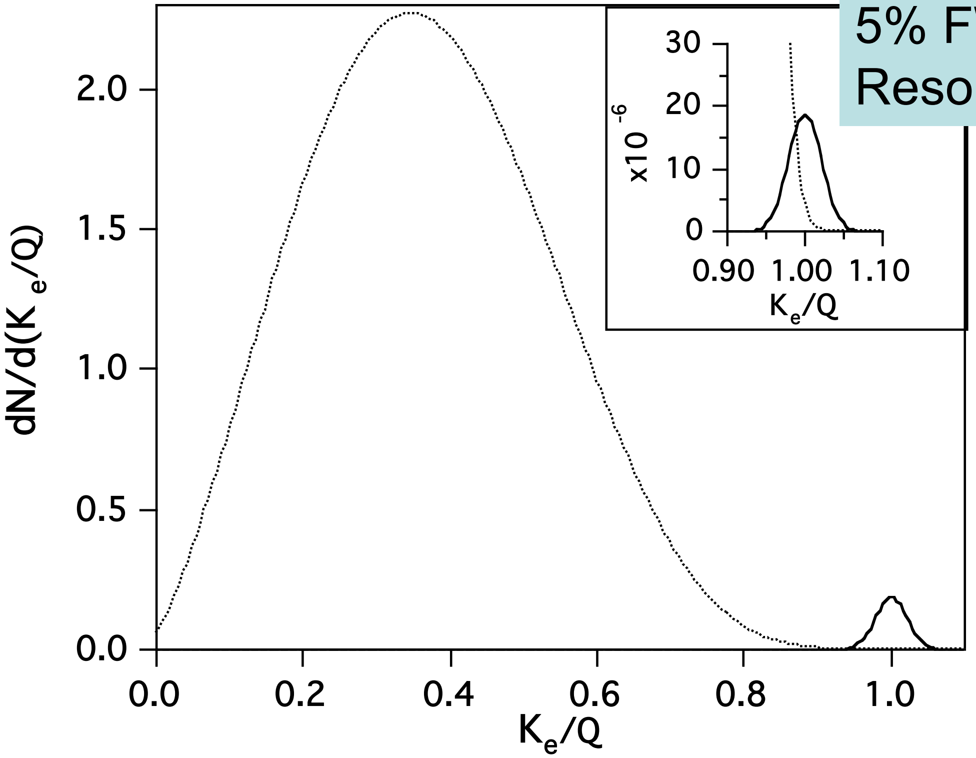
Reduction	Rejection
Low-inactive-mass design	Energy resolution
Ultra-pure materials	Array granularity
Clean handling	Pulse shape
Shielding and depth	Time correlation

The Importance of Energy Resolution



- ββ(2ν)
  - –For Ge-detector experiments, resolution is sufficient to prevent tail from intruding on peak. (0.12% FWHM)
  - –Resolution, however, is also a very important issue for signal-to-noise.
  - –Discovery potential sensitive to background and resolution.

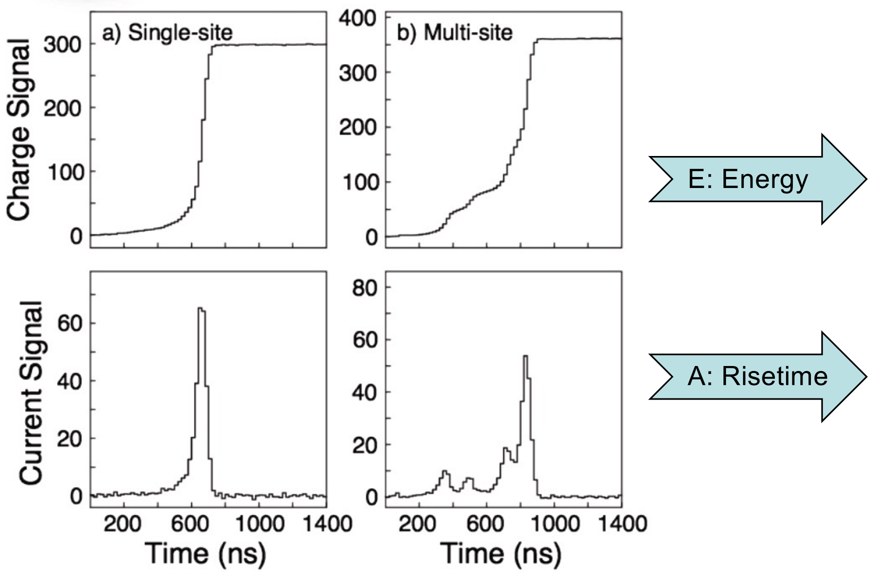
Example
5% FWHM
Resolution



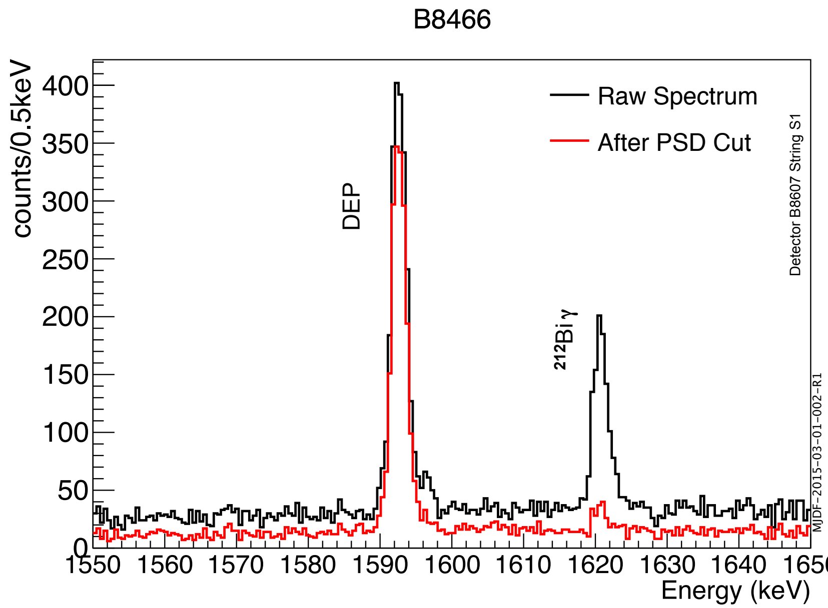
Pulse Shape Discrimination: A/E
ββ is a single-site energy deposit

Point-Contact Detectors

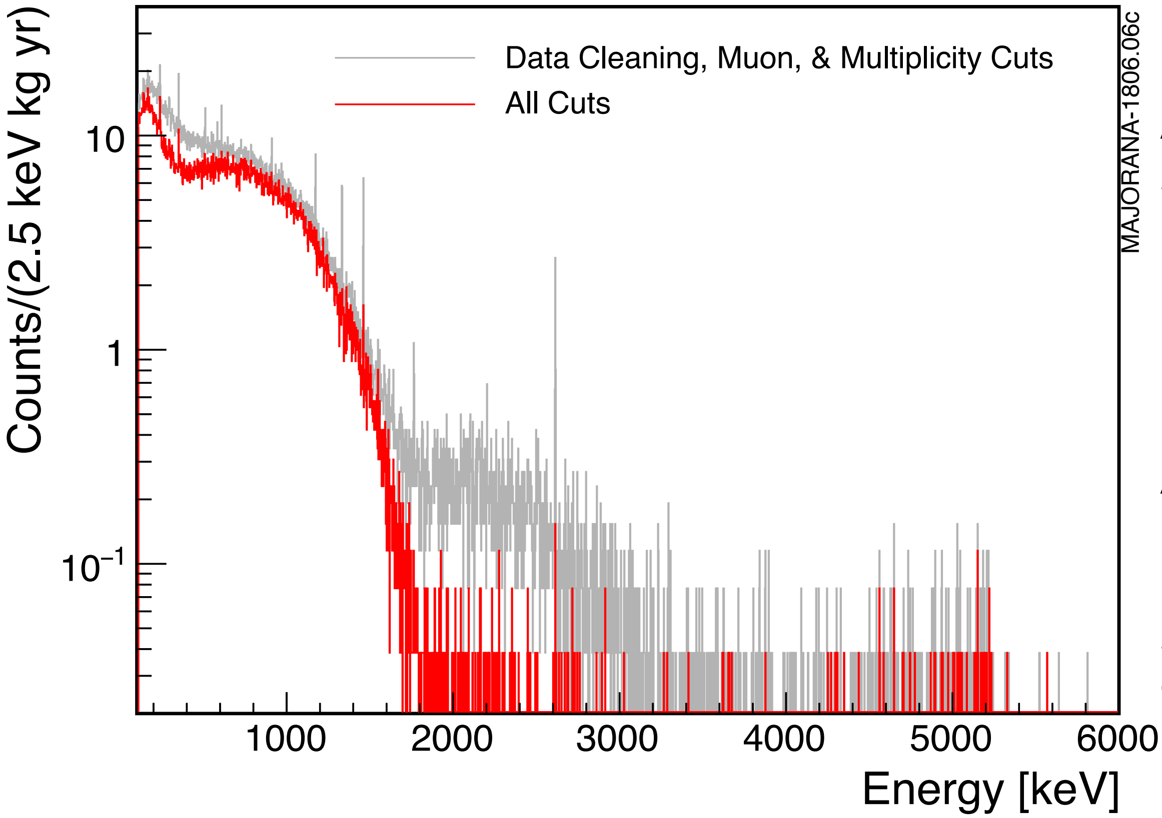
- Small central contact, low capacitance.
- Little wasted Ge.
- Localized weighting potential provides good multiple-site energy deposit rejection.



Natural BEGe detector in Prototype Cryostat



0νββ Result



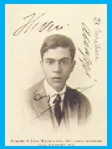
All data (open/blind) up to April 15, 2018
26 kg yr (^{enr}Ge)

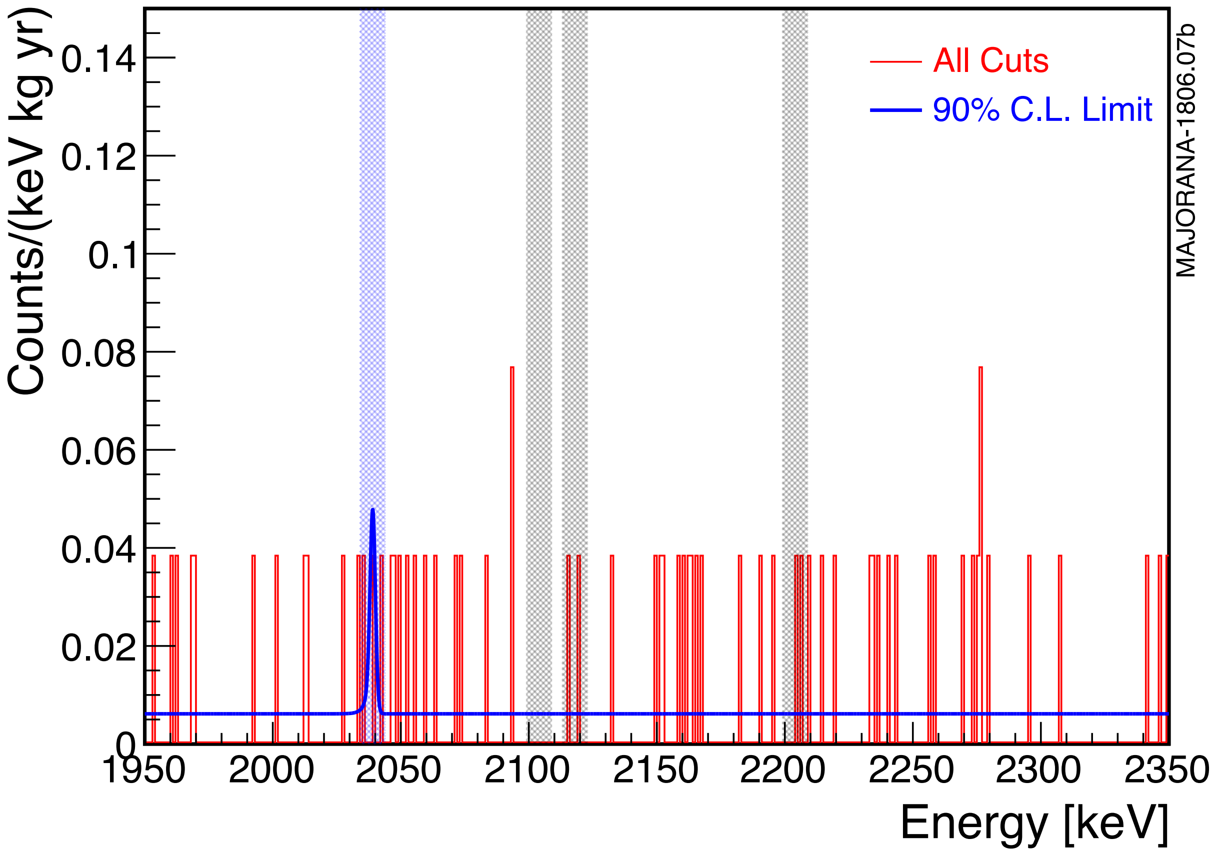
Full exposure background
15.4±2.0 counts/(FWHM t yr)

Expected counts in ROI (4.13 keV) 0.66
After unblinding: 1 event at 2040 keV

Lowest background configuration
21.3 kg yr, 11.9±2.0 counts/(FWHM t yr)
or $(4.7\pm0.8)\times10^{-3}$ counts/keV kg yr

The 0νββ Limit (PRL 120, 132502 (2018) / PRC 100 025501 (2019)))





Updated exposure (26 kg yr) limit: >2.7×10^{25} yr (90% CL)

Medium Sensitivity: 4.8×10^{25} yr

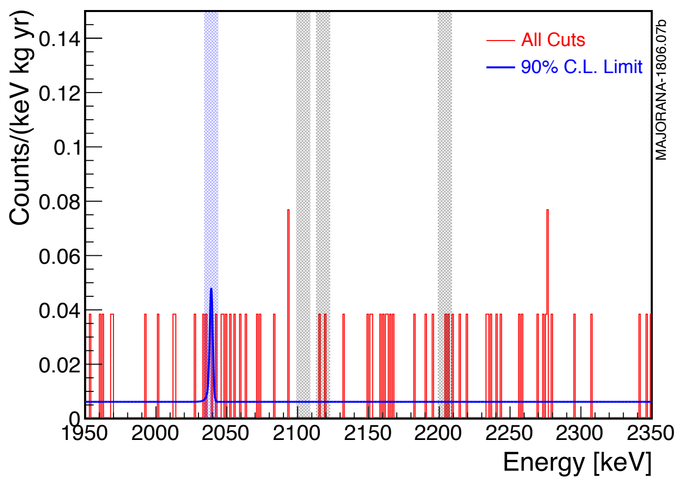
Total exposure being analyzed is ~65 kg yr.

15 MAJORANA papers so far
3 PRLs
~10 in various stages of preparation

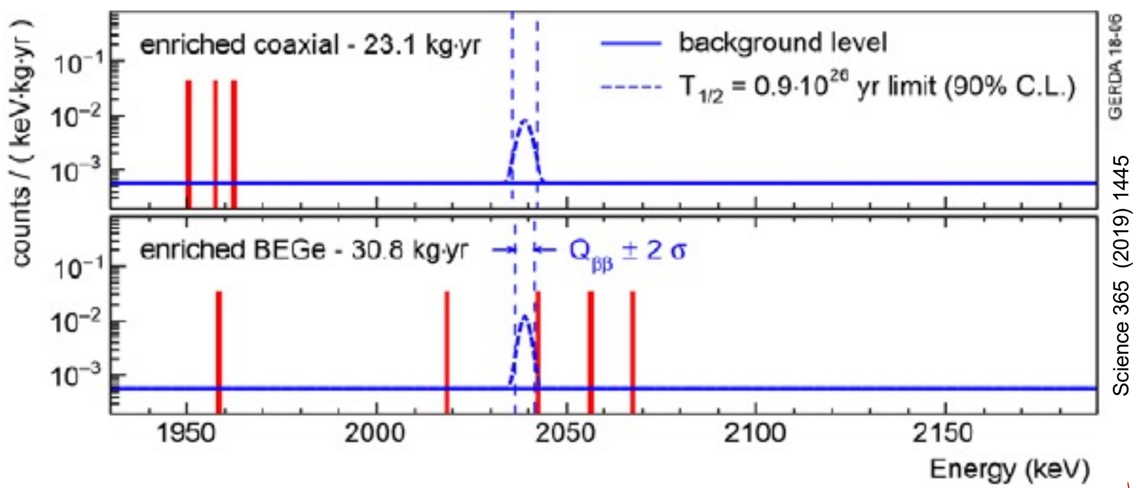
MAJORANA & GERDA

- Both experiments are presently operating “nearly background free” and benefiting from excellent energy resolution. Excellent limits with modest exposure.
- Limit >10^{26} yr .
- Only modest further background reduction is required for the next-generation Ge experiment.

Limit based on 26 kg yr
$T_{1/2} > 2.7\times10^{25}$ yr



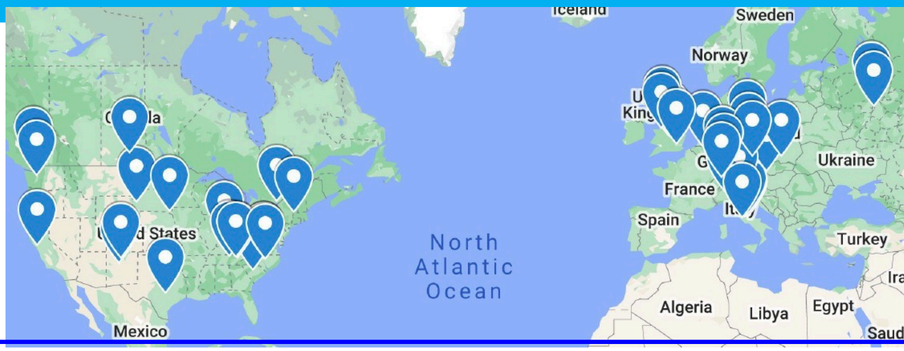
Limit based on 127.2 kg yr
$T_{1/2} > 1.8\times10^{26}$ yr



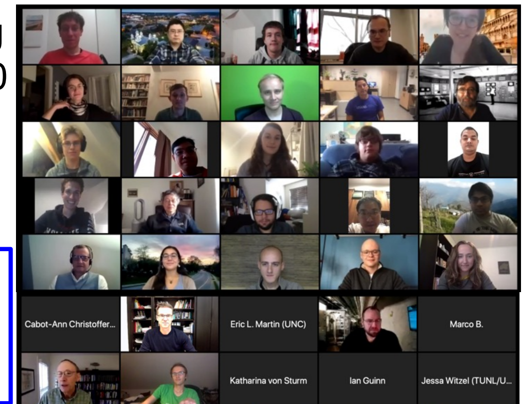
The Best of MAJORANA & GERDA

- MAJORANA
  - Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
  - Low noise electronics improves PSD
  - Low energy threshold (helps reject cosmogenic background)
- GERDA
  - LAr veto
  - Low-A shield, no Pb
- Both
  - Clean fabrication techniques
  - Control of surface exposure
  - Development of large point-contact detectors
  - Lowest background and best resolution $0\nu\beta\beta$ experiments

Large **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay – LEGEND
48 institutions, About 260 scientists



Collaboration Meeting
Nov 2020



LEGEND mission: "The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results."

Univ. New Mexico
L'Aquila University and INFN
Lab. Naz. Gran Sasso
University Texas, Austin
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Indiana University
Comenius University
Simon Fraser University
University of North Carolina
University of South Carolina
Tennessee Tech University
University of Warwick
Jagiellonian University
Technical University Dresden
Joint Inst. Nucl. Res.

Duke University
Triangle Univ. Nuclear. Lab.
Joint Research Centre, Geel
Max Planck Institute, Heidelberg
Queens University
University Tennessee
Lancaster University
University Liverpool
University College London
Los Alamos National Lab.
INFN Milano Bicocca
Milano University and Milano INFN
Institute Nuclear Research Russ. Acad. Sci.
National Research Center Kurchatov Inst.
Lab. Exper. Nucl. Phy. MEPhI
Max Planck Institute, Munich
Technical University Munich

Oak Ridge National Laboratory
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University South Dakota
Williams College
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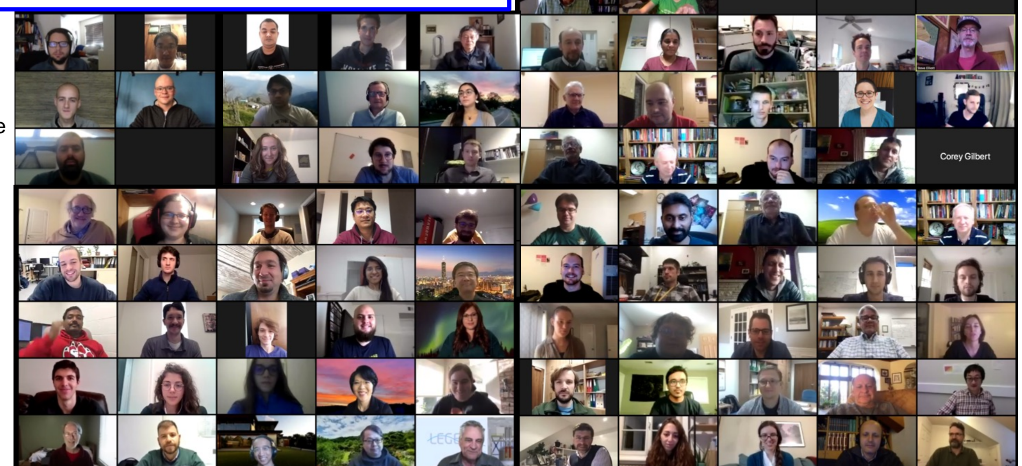
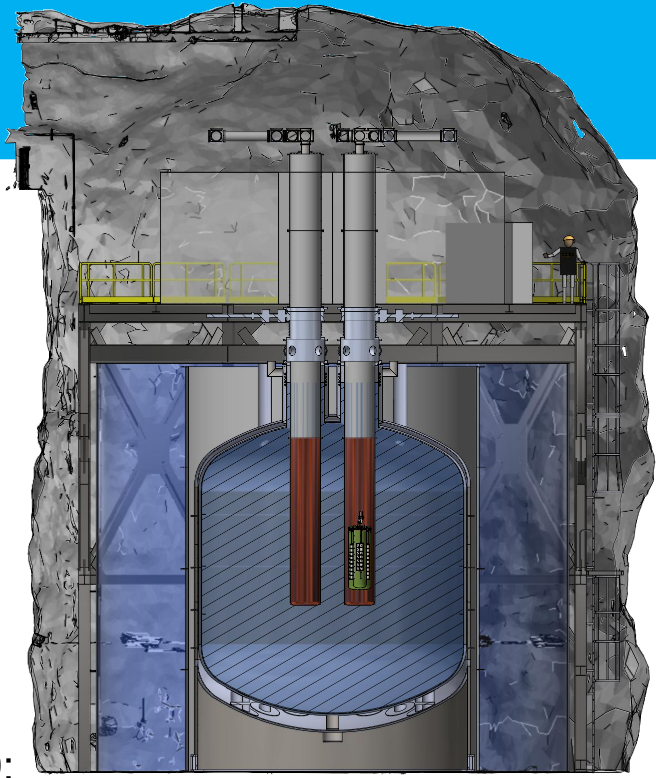


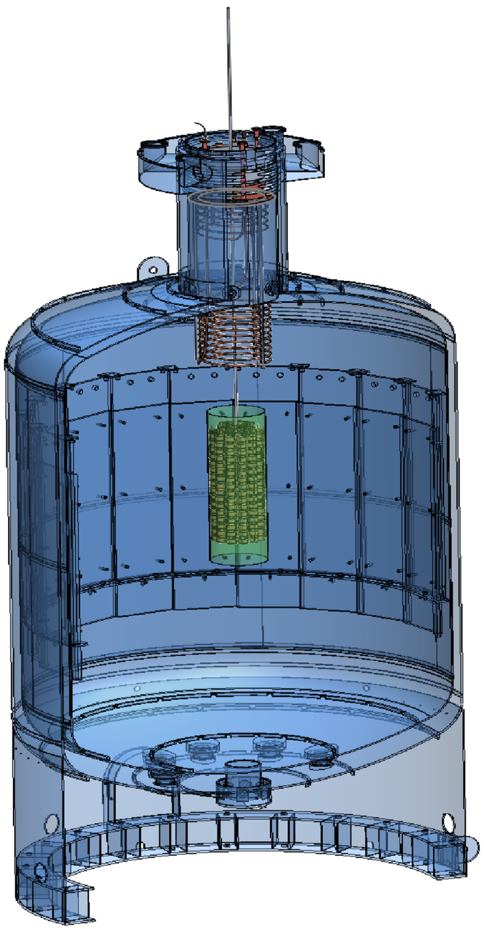
LEGEND (arXiv:1709.01980, pCDR to be posted soon)

LEGEND-200:
- 200 kg in upgrade of existing infrastructure at Gran Sasso
- Background goal 0.6 cts/(FWHM t yr)
- Data start ~2021



LEGEND-1000:
- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal <0.03 cts/(FWHM t yr)
- Location to be selected

LEGEND-200: MAJORANA/GERDA/New Det.

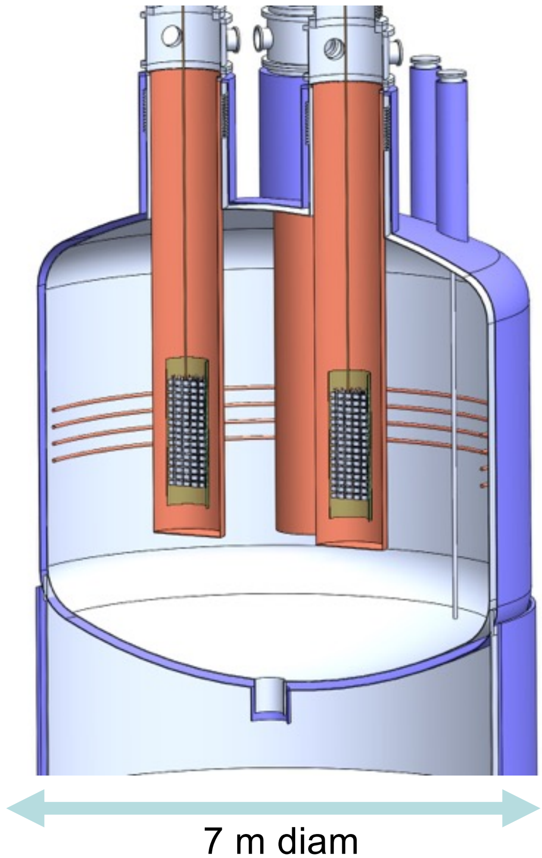


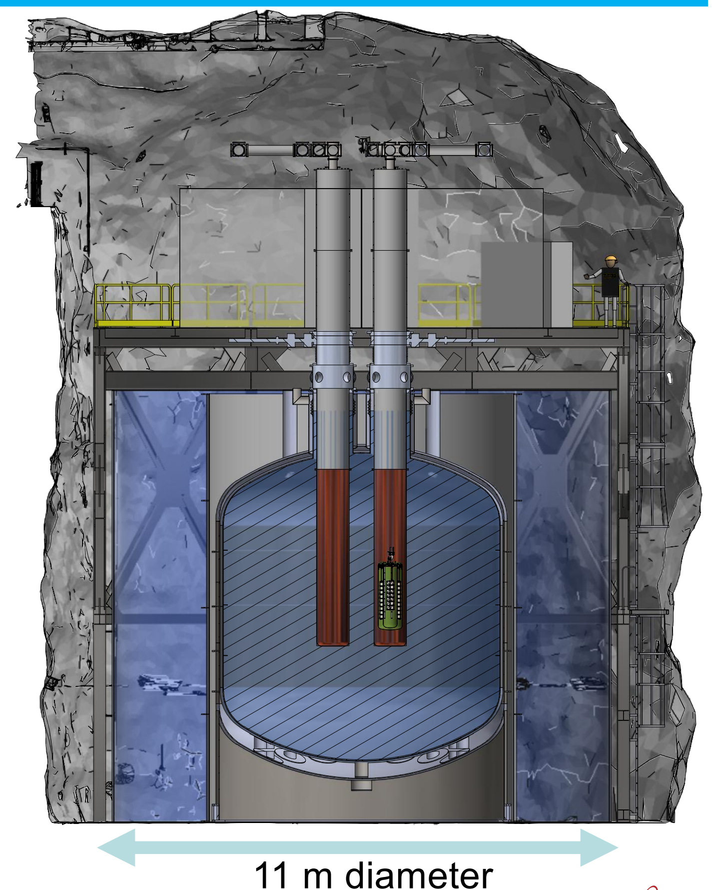
LANL Detector to Test / `Partial' LANL Detector

Urenco only material / Urenco mixed with ECP

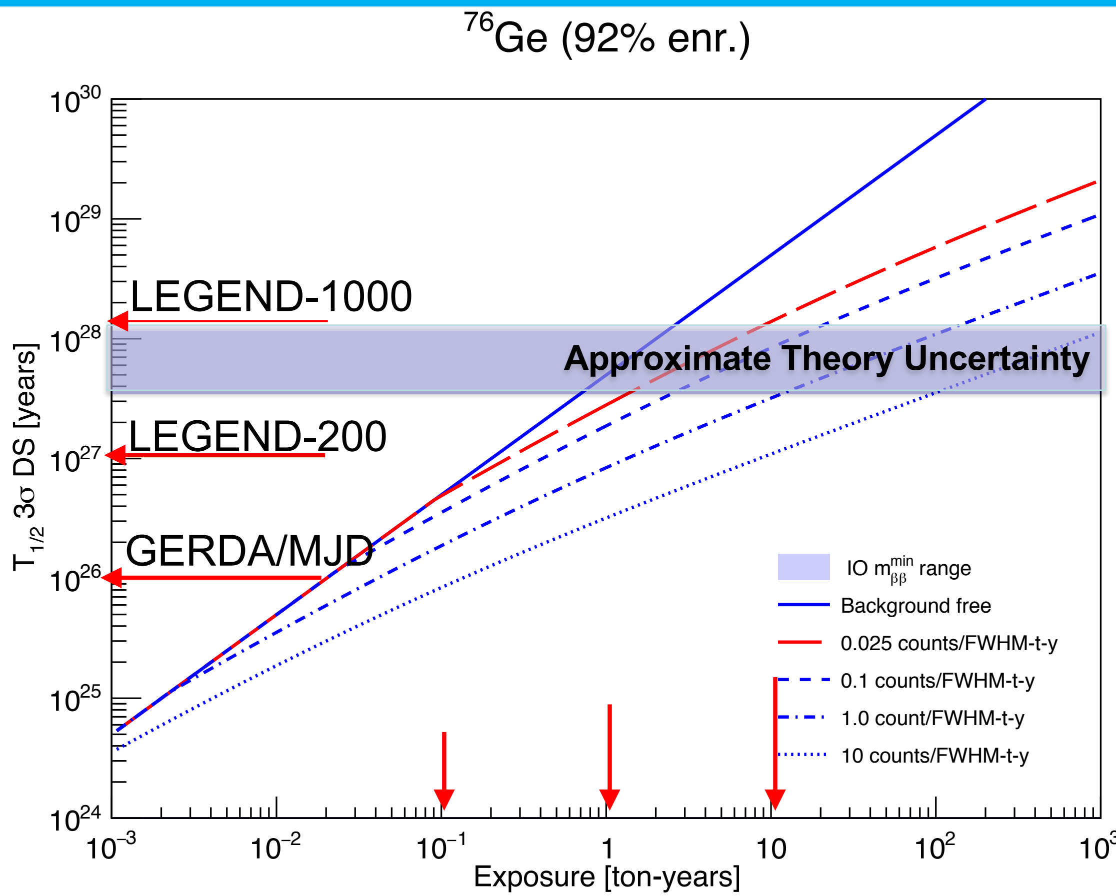
LEGEND-1000 Baseline Design

- 4 payloads of Ge detectors
  - 250 kg each
  - Data from each when deployed
  - 4 reentrant tubes on 2-m diam. circle. Tube radius is ~0.8 m
- Each payload surrounded by LAr depleted in Ar-39/Ar-42
- All payloads deployed within a cryostat of LAr. 7 m diam.
- This cryostat deployed with a water tank at least 11 m diam.





Ge Discovery Potential



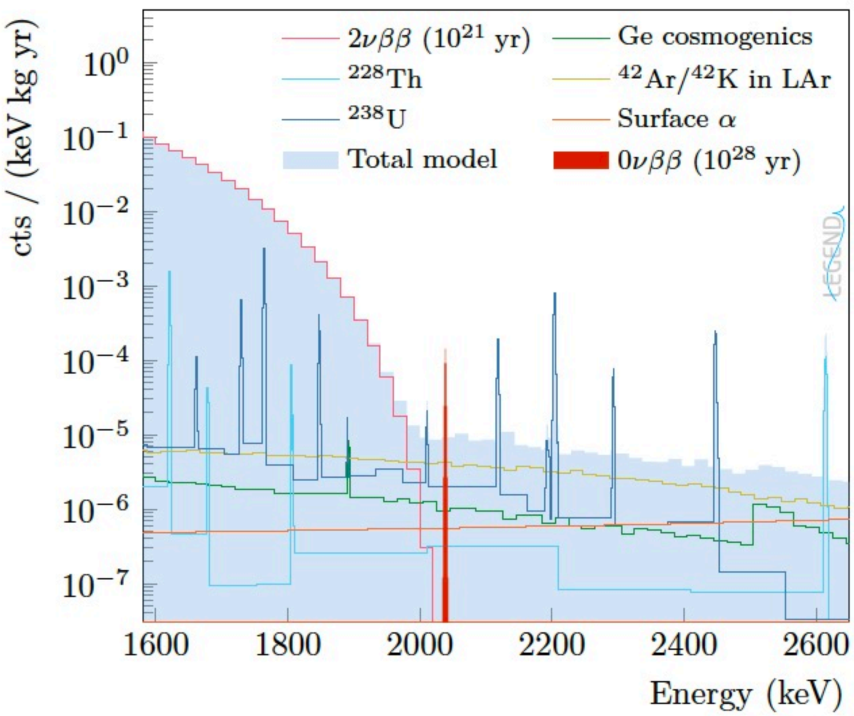
3σ discovery Level to cover inverted ordering, given matrix element uncertainty.

At DL, would have a 3σ discovery 50% of experimental trials.

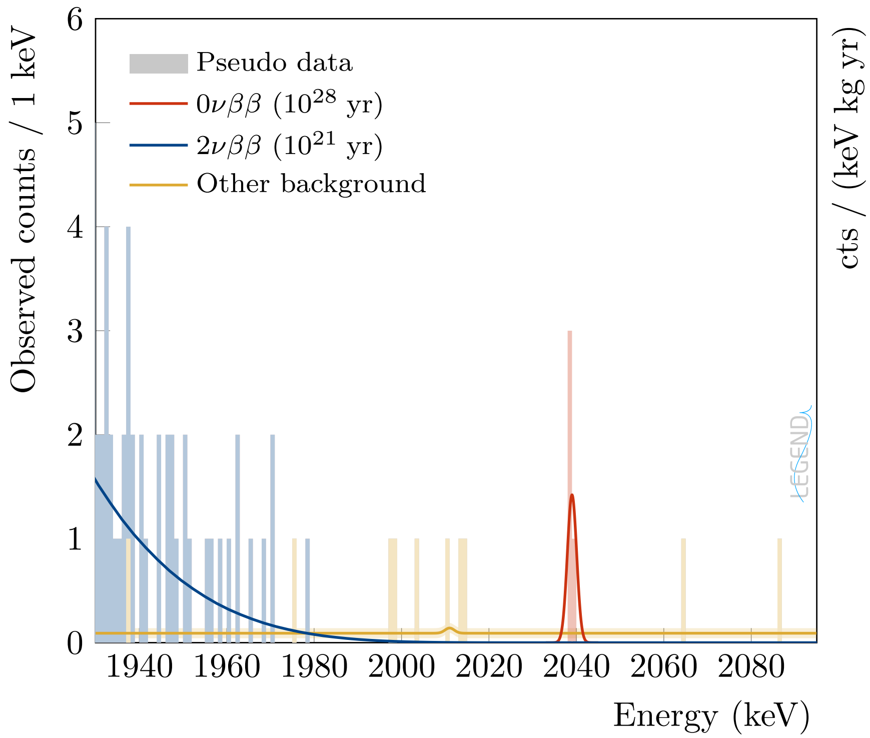
>1.3x10^{28} yr for 9-21 meV, depending on matrix element.

Simulated Spectra: Nearly Background Free

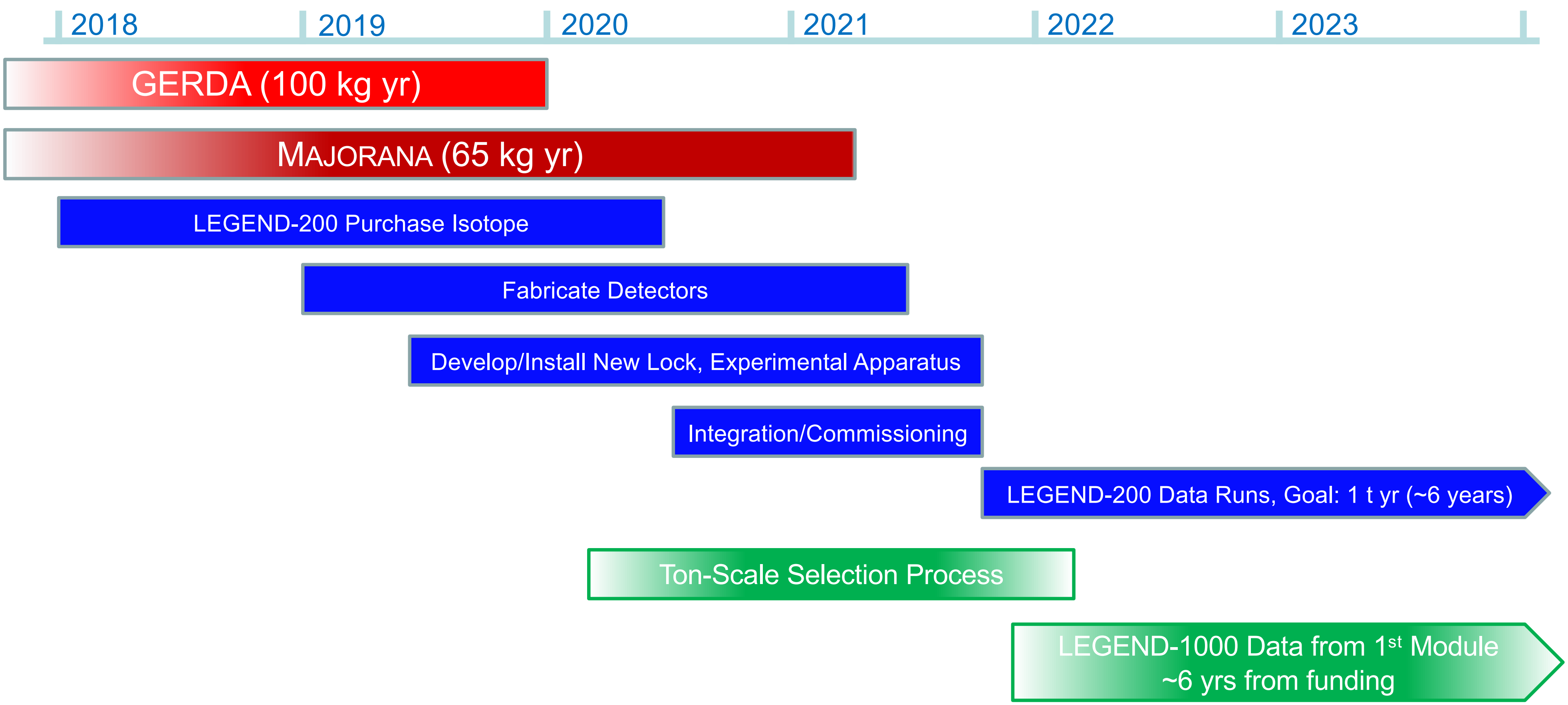
Calculated Predicted L-1000 Spectrum. After cuts. Note $2\nu\beta\beta$ dominates.



Example Toy Simulation Near Limit of Sensitivity. Peak is clear even with just a few counts.

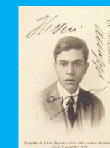


Schedules



2018
2019
2020
2021
2022
2023
GERDA (100 kg yr)
MAJORANA (65 kg yr)
LEGEND-200 Purchase Isotope
Fabricate Detectors
Develop/Install New Lock, Experimental Apparatus
Integration/Commissioning
LEGEND-200 Data Runs, Goal: 1 t yr (~6 years)
Ton-Scale Selection Process
LEGEND-1000 Data from 1st Module
~6 yrs from funding

LDRD: Key to our Success



- My definition of success
  - R&D under LDRD reduces risk in a proposal, leading to project funding for an experiment.
  - R&D that facilitates transition of program funding to new projects. SNO -> MAJORANA -> LEGEND-200 and next hopefully LEGEND-1000.
  - Provide workforce development opportunities for staff at all levels to build experience in key skills.
- Early, pre-funding MAJORANA design
  - Test stand to verify thermo-modeling led to complete re-think of how the detector would cool.
  - Prototype module with substantial number of detectors led to many mechanical design improvements.
  - Developed calibration system.
  - Developed additional vendors for larger point contact detectors, reducing cost. Saved MAJORANA about $1M.
- Early pre-funding LEGEND-200 R&D
  - Developed 2nd vendor for isotope production. Isotope cost ~20% lower for LEGEND-200 than MAJORANA.
  - The Europeans used this funding announcement to sway their agencies to fund LEGEND-200.
  - We used that development to sway NSF to fund LEGEND-200.
  - Led to DOE providing project support and a re-direction of our program funds.
- This basic science work attracts talent to the Laboratory
  - Postdocs, OSGSR, SULI, postbac program.
- This work provides LANL scientists with worldwide exposure and develops careers of young staff.
  - Many of our postdocs stay at LANL as staff in other groups/divisions.
  - We have developed leadership roles for our young (and old) people within these large collaborations.
  - Corresponding authors, task group leads, executive council membership, review committees, analysis leadership.

Summary

- Next generation $\beta\beta$ experiments are well motivated scientifically and technically.
  - Many technologies are advancing quickly.
- ^{76}Ge combines the best detector resolution and best backgrounds achieved to date.
- MAJORANA and GERDA have established the viability of proceeding with a phased approach to a 1000-kg ^{76}Ge experiment.
  - Only a modest improvement in background is required.
  - The 200-kg phase provides an opportunity for an early start to refine concepts and obtain science results.
- LDRD has played a strong role in this successful program.

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